UNIVERSITY OF COLORADO
Campus Box 311, Boulder, Colorado 80309–0311
Telephone (303) 492-6487 Fax (303) 492-6487

To: Dr. Don Anderson, NASA HQ

From: Murry Salby

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Subject: Final Report: NAG5-8311
Diurnal Cycle of Convection and Interaction with the Large-Scale Circulation
PI: Murry L. Salby
University of Colorado

Status:

The science in this effort was scheduled in the project's 3rd and 4th years, after a long record of high-resolution Global Cloud Imagery (GCI) had been produced. Unfortunately, political disruptions that interfered with this project led to its funding being terminated after only two years of support. Nevertheless, the availability of intermediate data opened the door to a number of important scientific studies. Beyond considerations of the diurnal cycle addressed in this grant, the GCI makes possible a wide range of studies surrounding convection, cloud, and precipitation. Several are already underway with colleagues in the US and abroad, who have requested the GCI.

- *Global Cloud Simulations* are being validated against the GCI at BMRC in Australia (L. Rikis, W. Bourke, and K. Puri). Simulated cloud cover is analyzed in several key geographical regions for its organization and space-time behavior a signature of its interaction with the general circulation. Figure 1 compares brightness temperature observed in the GCI against that forecasted by the BMRC GCM, both at 06Z on November 17, 1987. The GCM successfully simulates the large-scale organization of cloud by baroclinic systems at midlatitudes. However, it is problematic in the tropics, where cloud organization is cumulus in nature and less predictable. The region highlighted contains the Pacific ITCZ. Time series of areal-averaged cloud fraction over this region are shown in Fig. 2. In the GCI (Fig. 2a), it is dominated by variations of 2–8 days, corresponding to easterly waves that organize convection inside the ITCZ. In the model (Fig. 2b), on the other hand, such variations are small, overshadowed by the diurnal cycle even though the region is almost entirely maritime. The distinction emerges clearly in the frequency spectrum (Fig. 3). Variance in the GCI (Fig. 3a) has a red distribution, broadly peaked at periods of 4–8 days. However variance in the model (Fig. 3b) is sharply concentrated at low frequency and at the diurnal – the two forms of systematic cloud variations. Missing is almost all of the variance at intermediate periods, which characterize the organization of cloud by unsteady elements of the general circulation. Similar behavior is found in the NCAR CCM. Other important discrepancies are revealed by histograms of cloud fraction (Fig. 4): In the GCI (Fig. 4a), cloud fraction decreases steadily with brightness temperature (cloud height). A small but significant fraction is observed at temperatures colder than 205 K, reflecting the highest cloud and penetrative convection that maintains the tropopause (see below). The model (Fig. 3b), on the other hand, has too much warm (low) cloud, and none above 235 K.

  These discrepancies have pointed to deficiencies in the parameterization of convection, as well as of cloud microphysics that enter the model's calculation of brightness temperature. As part of a bi-national collaboration, this study is continuing with the GCI (see below). It uses the BMRC medium resolution (T79) model, shown above, as well as a high-resolution (T239) version, which has resolution approaching that of the GCI.

- *A Global Precipitation Product* has been produced from the GCI, anchored in the GPCP monthly-mean climatology (which is based on cloud cover, the sparse distribution of rain gauges, and microwave measurements over ocean). This 3-hourly product is produced by regressing cold cloud fraction in the GCI onto monthly-mean precip in the GPCP climatology. It yields areal-averaged precipitation, at 2.5° and 3-hourly resolution, that has the same time mean as the GPCP climatology. However, the GCI/GPCP product contains information well beyond the time mean, resolving the unsteady organization of precipitation by elements of the general circulation, like easterly waves in the ITCZ, the Madden-Julian oscillation, the diurnal cycle, and developing baroclinic systems in the storm tracks.

- *Global Precipitation Simulations* are being validated against the GCI/GPCP product at COLA (J. Kinter, D. Straus, B. Kurtman). Figure 5 compares time series of areal-averaged precip over the Pacific ITCZ (cf. Fig. 1) in the GCI/GPCP product against that simulated for the same period by the COLA GCM. In the GCI (Fig. 5a), areal-averaged precip has a mean of 4 mm/day and it varies over time scales of 2–8 days, characteristic of easterly waves that punctuate the ITCZ. The model precip (Fig. 5b), on the other hand, has a mean approaching 7 mm/day and is again strongly diurnal, with little of the organization on intermediate time scales that is present in the data. The distinction emerges clearly in frequency spectra of areal-averaged precip (Fig. 6). In the GCI/GPCP (Fig. 6a), the distribution of variance is red, with a broad peak at periods of 2–8 days. However, in the model, variance is again sharply concentrated at low frequency and at the diurnal. Missing is almost all of the variance at intermediate periods, reflecting little interaction with the circulation.

  As with validating cloud simulations, these discrepancies have pointed to deficiencies in the treatment of convection and radiation, which influence surface heating, atmospheric stability, and the diurnal cycle. They are being pursued with the GCI/GPCP product to improve the simulation of precip.

- *Upper Tropospheric Humidity* (UTH) observed by MLS on board UARS (soon to be on board AURA) is being studied at ASA (F. Sassi, P. Callaghan), where it is being used jointly with the GCI to relate the occurrence of deep convection and cold cloud to humidification of the upper troposphere. Both have been used to investigate the collective impact of UTH and cold cloud on the energy budget and greenhouse effect. A related study at Caltech/JPL (Y. Yung) uses the GCI in similar applications.

- *Asynoptic Sampling Studies* are being supported by the GCI in the development and validation of satellite gridding algorithms: (1) to evaluate the bias in time-mean climate properties introduced by undersampling the diurnal cycle of convection and (2) to synoptically map convective structure that is undersampled by an individual satellite platform. These studies sampled realistic space-time behavior in the GCI, against which data products are validated. They have led to the development of a procedure that enables sparsely-sampled data from TRMM, MLS, and CLOUDSAT to be synoptically mapped, opening such data to a wide range of studies. An invited paper on the subject was presented at the INTERFACE Conference on statistics and satellite data analysis (Montreal, 2002). A similar paper is scheduled for the upcoming SPIE Conference on remote sensing of cloud (contingent on the availability of travel funds).

- *Convective Organization Studies* are being supported by the GCI at NCAR (L. Riccardiulli), where the the unsteady cloud field is being used to investigate divergence forcing in the tropics and the modulation of deep convection.

- *Equatorial Wave Simulations* are being validated against the GCI with NCAR CCM3 (R. Garcia), in which convective heating is being compared against the high-resolution description available from the GCI.

- *The Tropical Tropopause* and transport across it have been investigated with the GCI at NCAR (A. Gettelman), where penetrative convection is being studied in cold cloud observed above the local tropopause. Along with calculated heating rates, this yields estimates for convective exchange of tropospheric and stratospheric air.

Beyond using the data, many of these studies rely on the interactive Image Analysis System (IAS) that we developed to analyze space-time behavior in the GCI. The IAS provides a suite of space-time analyses to diagnose unsteady convective behavior. And it performs those analyses fast enough to be interactive. This system is accessed remotely by off-site collaborators (e.g., at COLA, BMRC, and NCAR).

Toward this end, the IAS has been converted from its single-user hardware platform to a software platform that can simultaneously accommodate multiple users. Until now, the formidable operations behind analyses like those in Figs. 2–6 could be performed efficiently only on specialized hardware, in which FFT and image functionality are *hardwired*.[1] However, rapid advances in RISC computer architecture make it now feasible

[1] Power spectra like those in Figs. 3 and 6 require transforming some 3000 time series each 1024 long.

to perform those operations on the new generation Alpha CPU. The IAS has been installed on a workstation with 4 Alpha CPUs, where it can support multiple users. The conversion entirely to software also enables the IAS to be installed locally at the sites of collaborators.

Outlook:

Climate modelers are keen to have a record with high time resolution to validate simulations of convection, in particular, surrounding elements of the general circulation, like mesoscale convective systems, the diurnal cycle, and baroclinic systems in the storm tracks. At the same time, such studies require a long and continuous record, which enables interannual changes to be investigated. The modelers are particularly enthusiastic over having such information for precip on a global basis. Several have expressed interest in seeing both records extended as long as possible. So has the group at MIT studying cloud electrification. In addition, the GCI appears in the recent *Encyclopedia of Atmospheric Science*, published by Academic Press.

14 years of GCI has been produced, providing a continuous record of 3-hourly global imagery that spans a decade and a half. The entire record is being subjected to the final stage of processing: Quality Control. Each of the global cloud images is visually inspected for intercalibration errors, exaggerated limb brightening, and mis-navigated satellites. These errors occur sporadically due to instrumental errors in the individual satellites. They must be treated *manually* for each of the ~ 45,000 images: An affected region of an individual image is windowed and then spatially filtered to separate large-scale coherent error from small-scale cloud structure. The technique successfully eliminates instrumental error, while leaving genuine cloud structure unaffected. In so doing, it yields global cloud imagery that is uniformly clean, largely free of the foregoing forms of error. As it requires manually treating an enormous volume of images, this final stage of GCI processing is being performed by half a dozen undergraduate students. They apply the technique through a mouse-driven Graphics User Interface (GUI), which enables an individual image to be corrected in a couple of minutes. When completed, the entire record of GCI will be archived on CD-ROMs and made available to the scientific community.

Regretably, support for this important work has expired. Owing to the political disruption that it experienced earlier, this project received only 2 of its 4 years of funding. The individual who obstructed this project has since resigned. His replacement has restored a stable environment in which this work can be pursued. As several researchers have expressed keen interest in the final record of GCI, we hope to reestablish support for this work to complete the final processing of the 14-yr record, to extend it to 2 full decades, and to perform the scientific component of this study that was originally to have been undertaken in years 3 and 4. That work will be proposed to an upcoming NRA for this program, the release of which we are awaiting.

Publications:

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Sassi, F., Salby, M., and W. Read, 2001: Relationship between upper-tropospheric humidity and deep convection. *J. Geophys. Res.*, **106**, 17,133-17,146.

Gettelman, A., Salby, M., Randel, W., and F. Sassi, 2001: Convection in the tropical tropopause region and stratosphere-troposphere exchange. *SPARC Newsletter*, **17**, 22-25.

Sassi, F., Salby, M., Pumphrey, H., and W. Read, 2002: Influence of the Madden-Julian oscillation on upper-tropospheric humidity. *J. Geophys. Res.*, (In Press).

Gettelman, A., Salby, M., and F. Sassi, 2002: Distribution and influence of convection near the tropical tropopause. *J. Geophys. Res.* (In Press).

Salby, M., F. Sassi, P. Callaghan, W. Read, and H. Pumphrey, 2002: Cloud, humidity, and thermal structure near the tropical tropopause. Part I: Relationship to deep convection. *J. Climate* (Submitted).

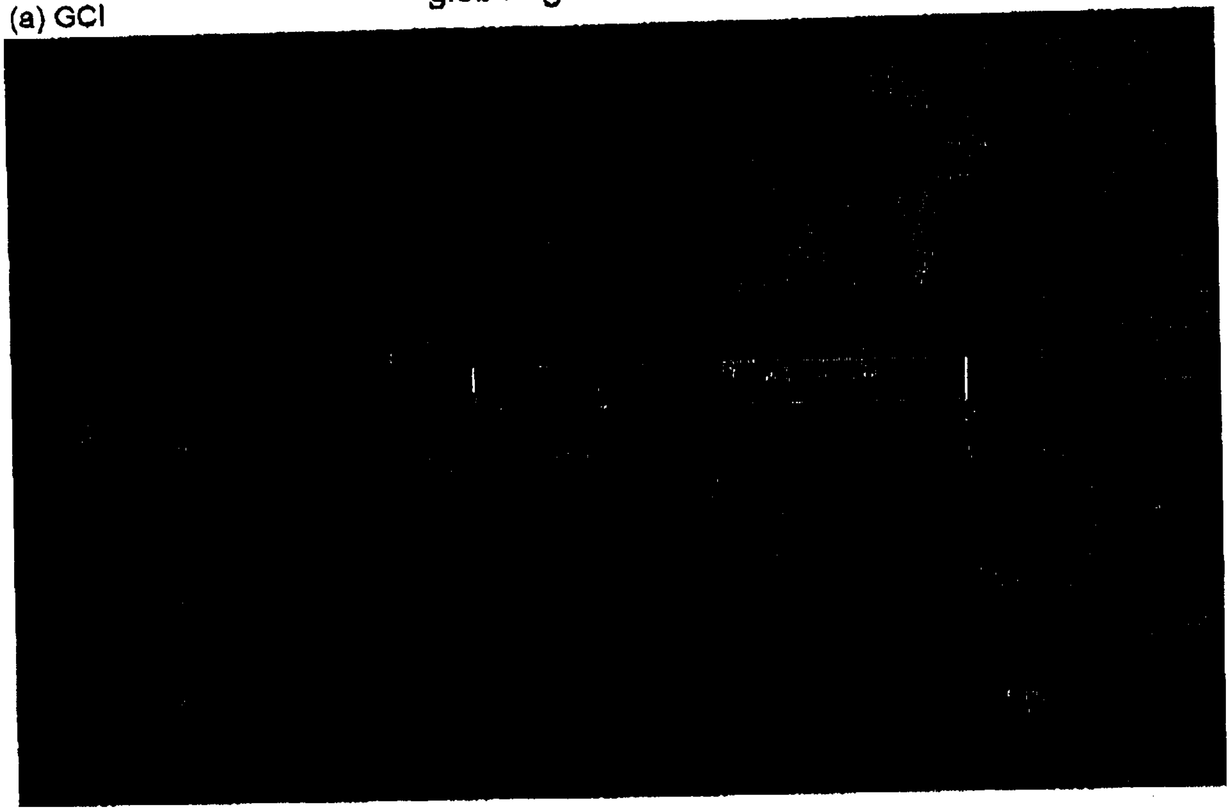
Salby, M., F. Sassi, P. Callaghan, W. Read, and H. Pumphrey, 2002: Cloud, humidity, and thermal structure near the tropical tropopause. Part II: Implications for water vapor and stratospheric transport. *J. Climate* (Submitted).

Callaghan, P., Salby, M., and F. Sassi, 2003: Relationship between cold cloud and moist static energy. *J. Climate* (Submitted).

Salby, M. and P. Callaghan, 2003: Control of the tropical tropopause and vertical transport across it. *J. Atmos. Sci.* (Submitted).

(a) GCI

globes/globe26.8732106



(b) BMRC Model

mglobes/globe26.8732106

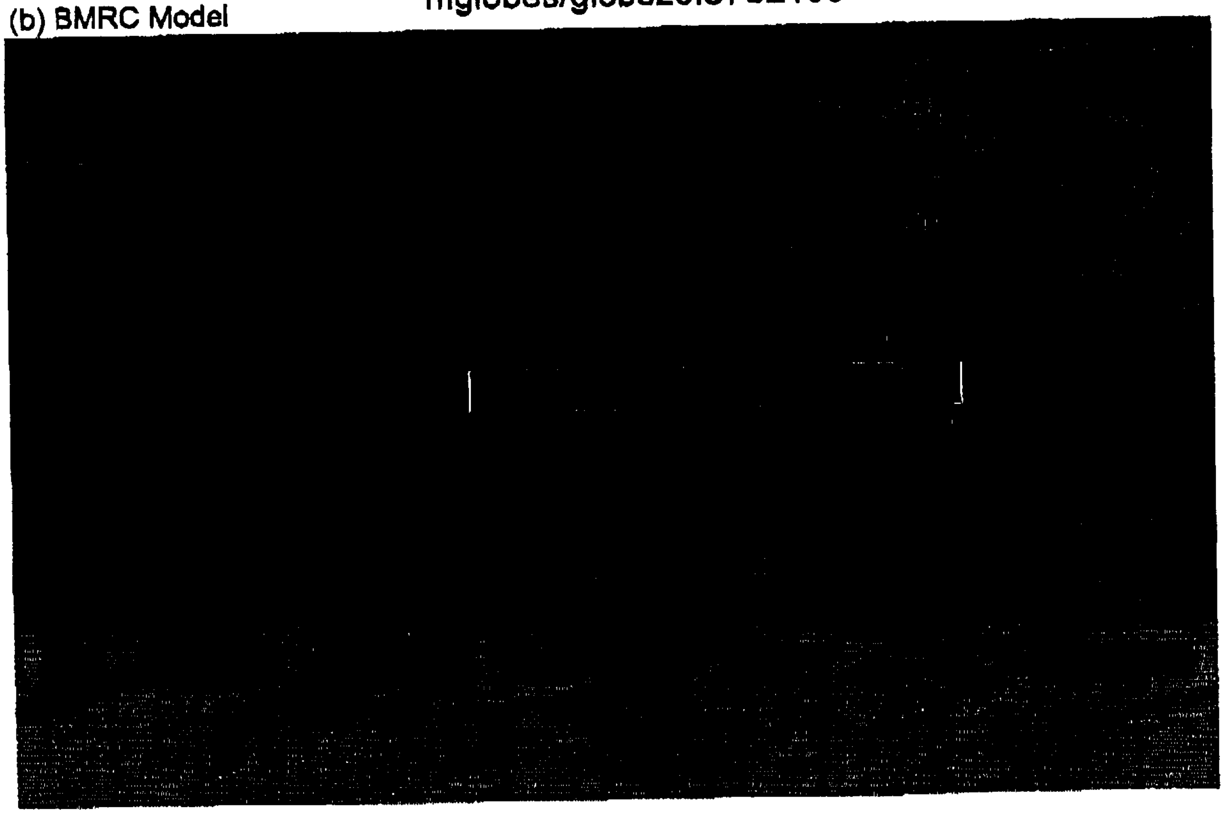


Figure 1: Synoptic (instantaneous) global distribution of brightness temperature at 06Z on November 17, 1987 (a) observed in the GCI and (b) simulated by the BMRC model.

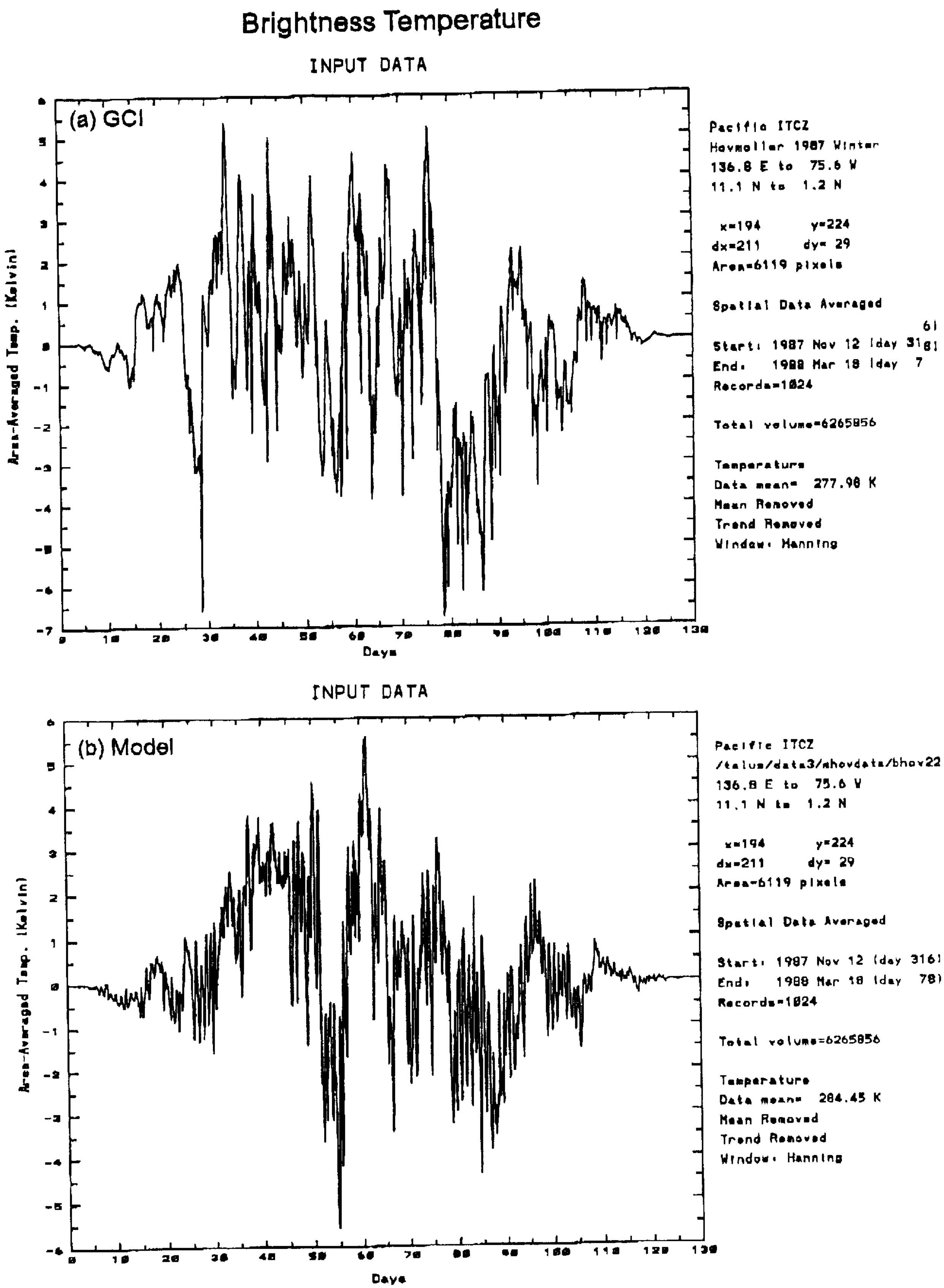


Figure 2: Time series of areal-averaged brightness temperature over the Pacific ITCZ (indicated in Fig. 1) during November 1987 -- March 1988, following application of a Hanning window, in (a) the GCI and (b) the model.

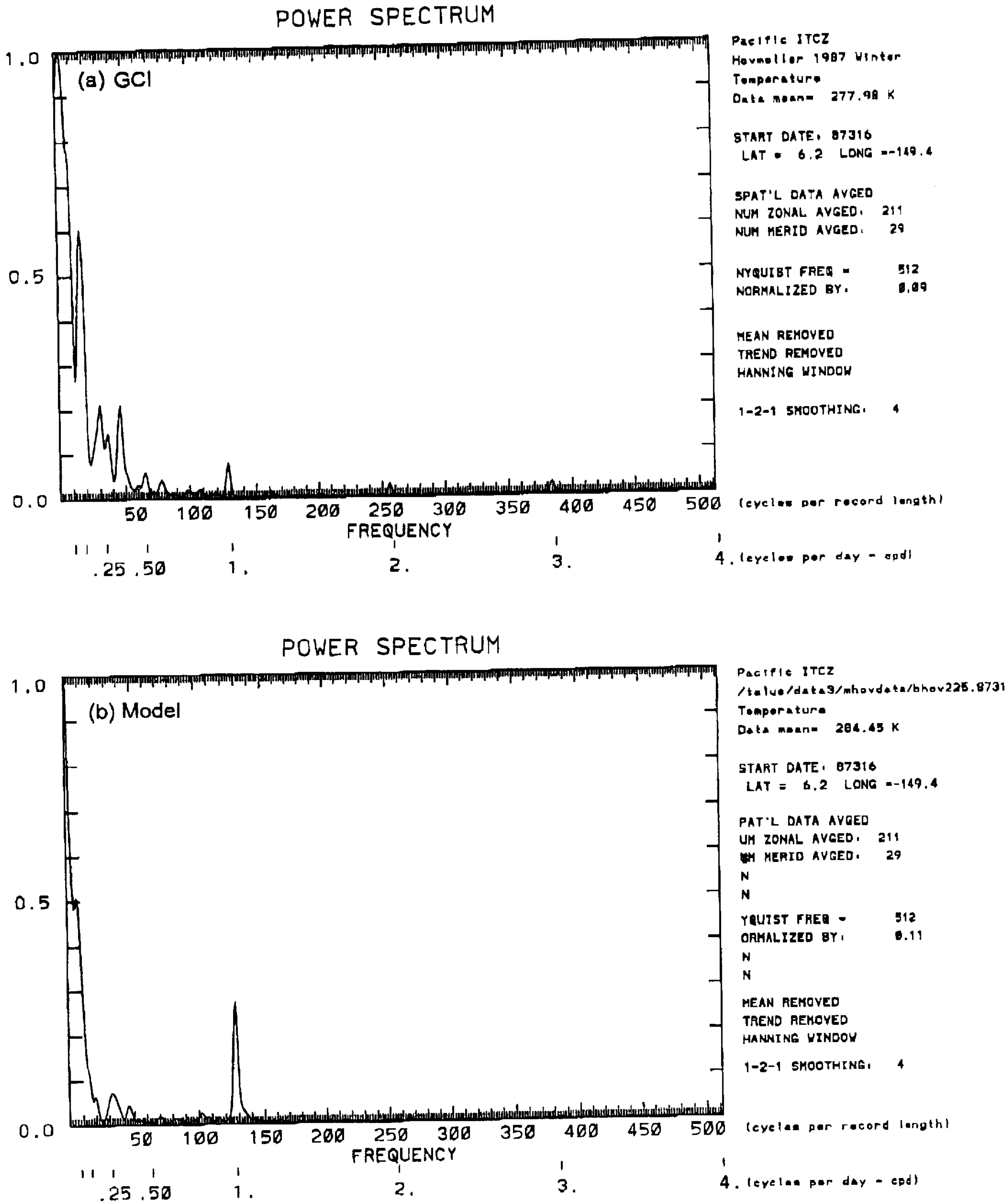


Figure 3: Power spectra, as a function of frequency, for areal-averaged brightness temperature over the pacific ITCZ in (a) the GCI and (b) the model.

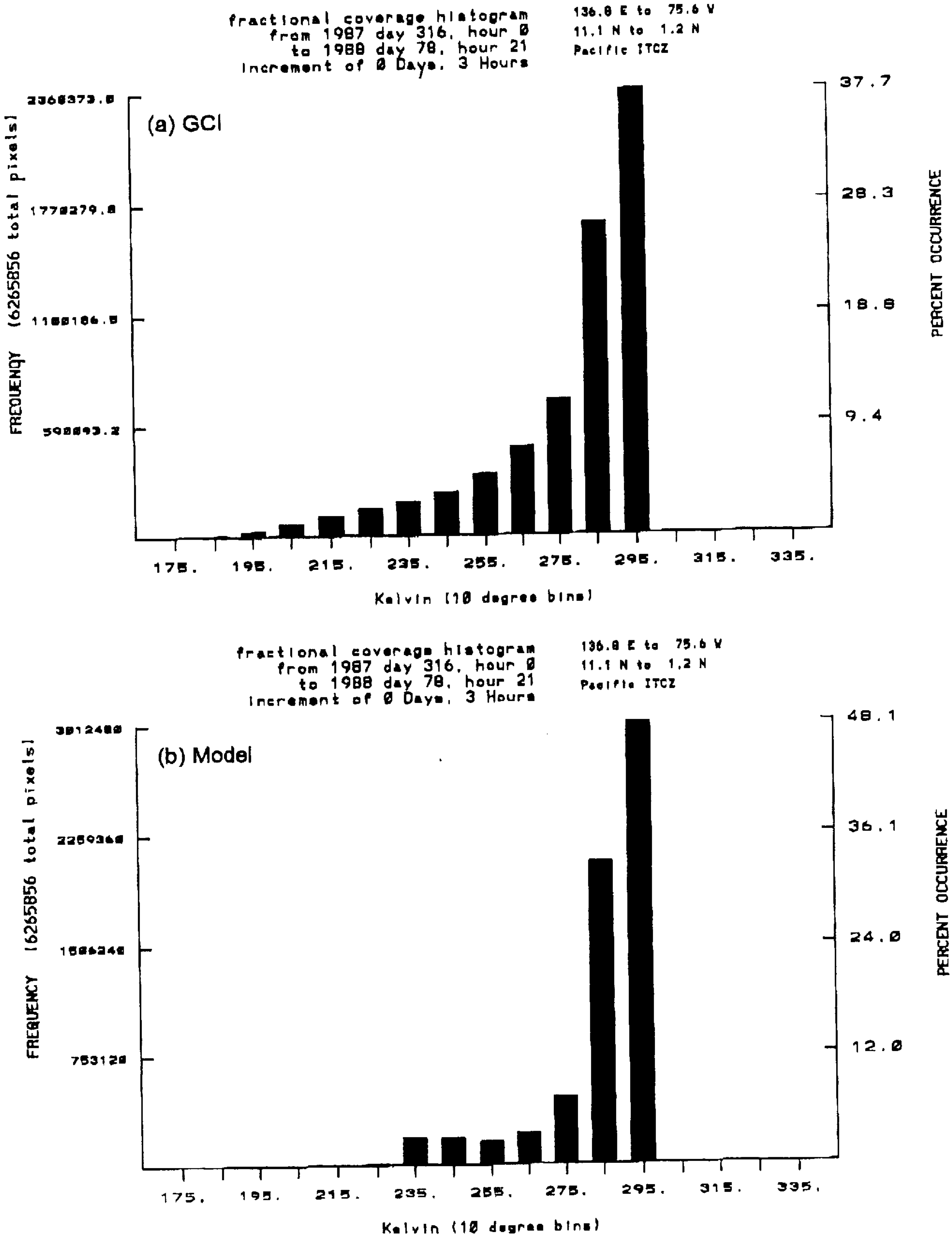


Figure 4: Distribution of cloud fraction over the pacific ITCZ during the season in Fig. 2 in (a) the GCI and (b) the model.

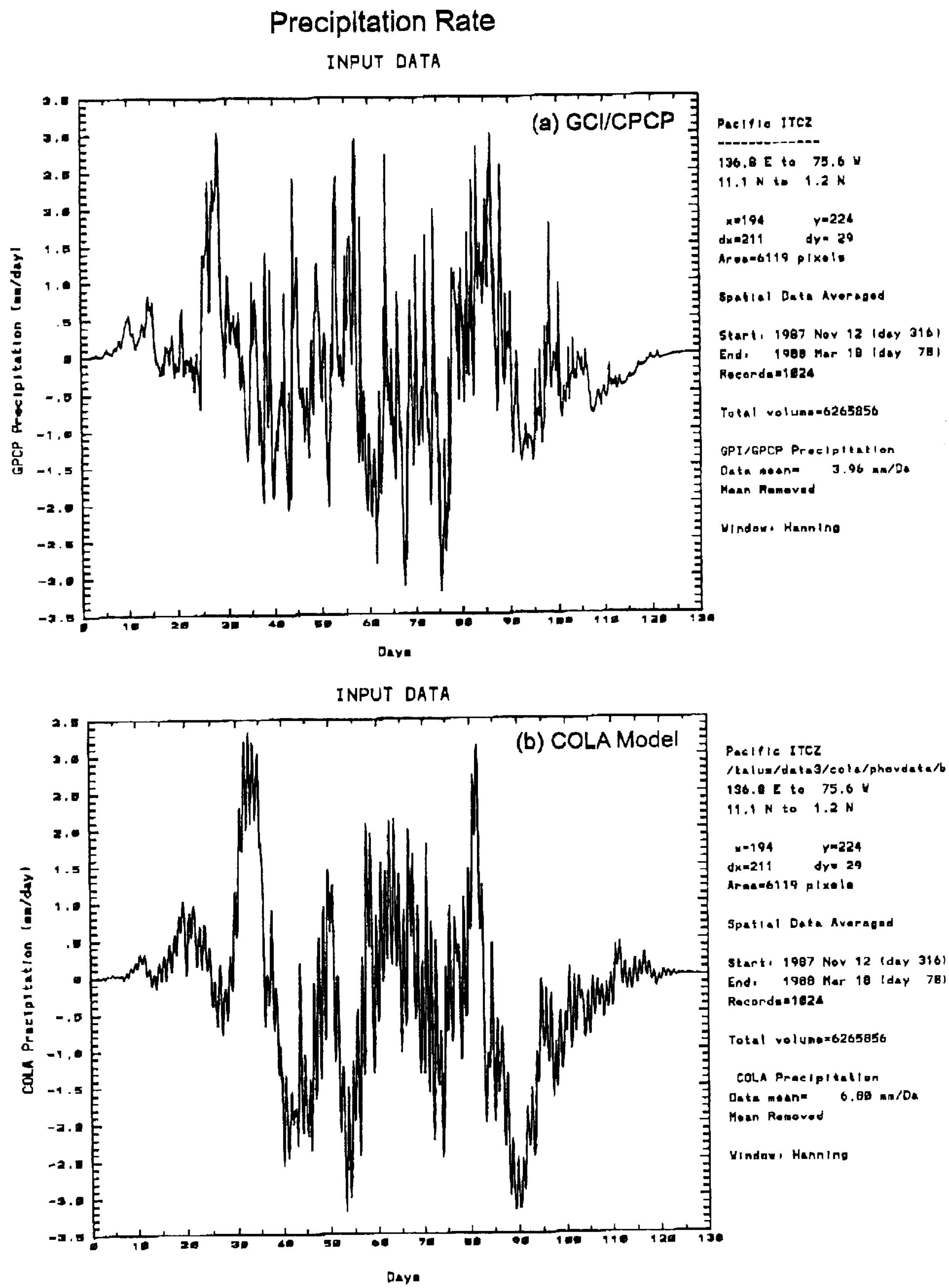
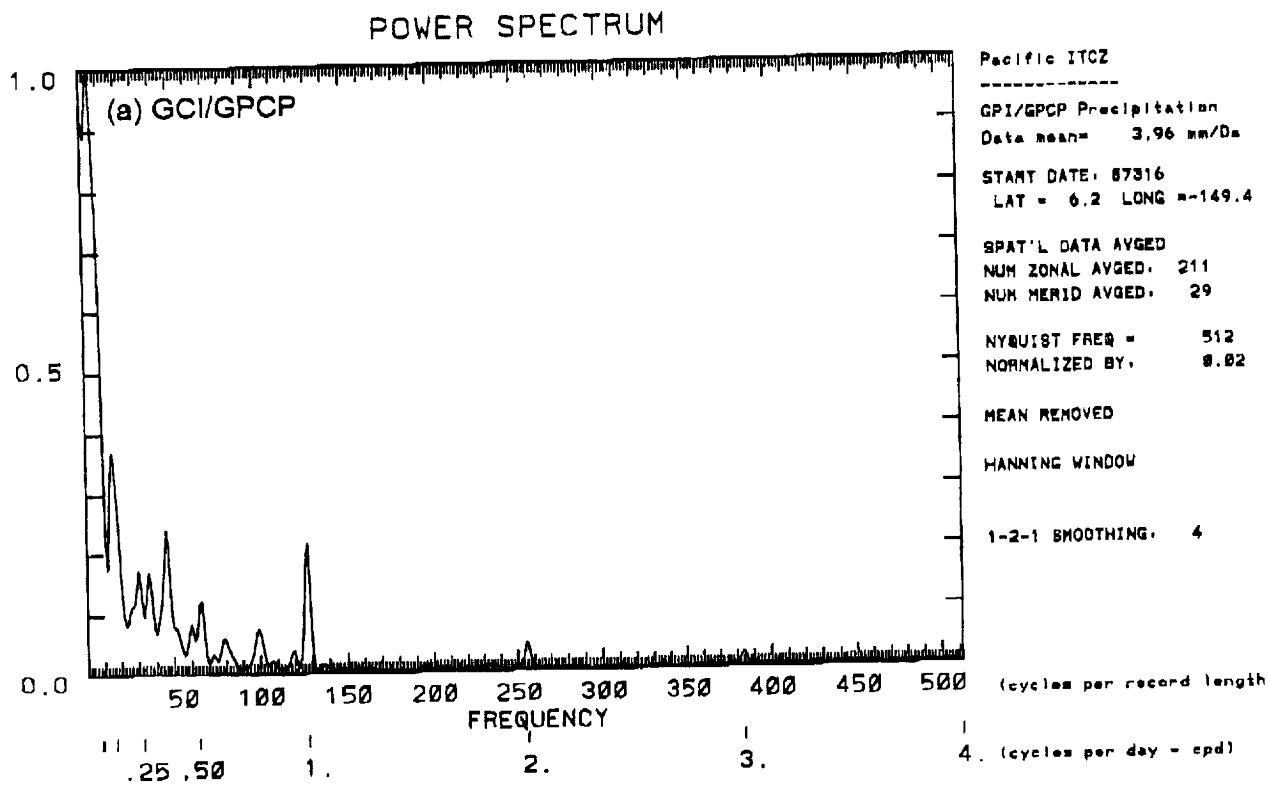


Figure 5: Time series of areal-averaged precipitation over the Pacific ITCZ during November 1987 -- March 1988, following application of a Hanning window, in (a) the GCI/GPCP and (b) the COLA model.



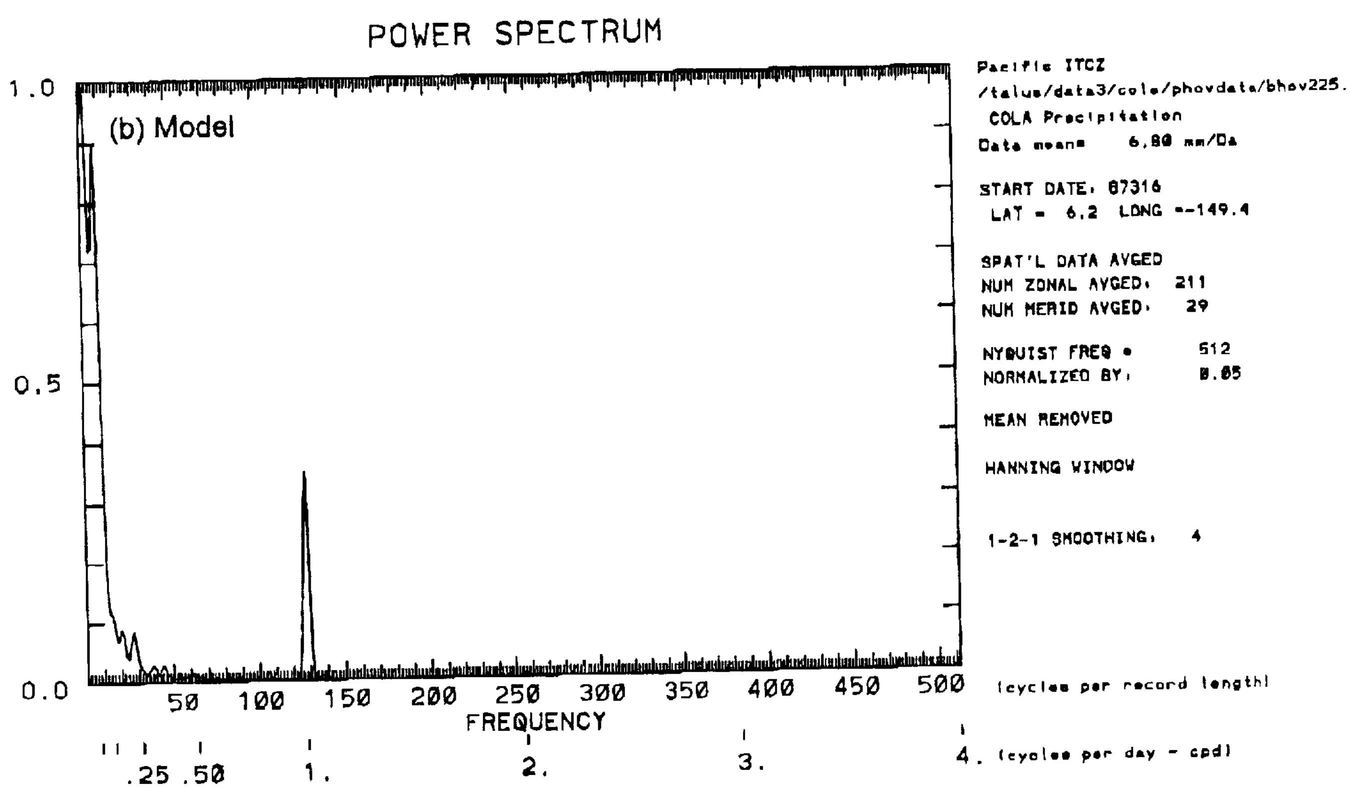


Figure 6: Power spectra, as a function of frequency, for areal-averaged precipitation over the pacific ITCZ in (a) the GCI/GPCP and (b) the model.